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# THE ICELANDIC 'ROFABARD' SOIL EROSION FEATURES

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## ABSTRACT

Soil erosion and desertification are severe problems in Iceland. Erosion processes are numerous, and more than one can occur at each site, resulting in many erosional forms. Erosion forms and an erosion severity scale are the basis for a recent national survey of erosion in Iceland. One of the most distinctive erosion forms in Iceland is an erosion escarpment, termed 'rofabard' in Icelandic. Rofabards are formed in thick but non-cohesive Andosols that overlie more cohesive materials such as glacial till or lava. The relatively loose Andosols beneath the root mat are undermined, creating escarpments, or rofabards. The rofabards retreat as a unit, with a fully vegetated and rich ecosystem on top but leaving barren desert in their place. Rofabards are common within a 20 000 km$^2$ area. The Agricultural Research Institute and Soil Conservation Service erosion database suggests that erosion associated with rofabards has denuded 15 000 –30 000 km$^2$ of land that was previously fully vegetated and had fertile Andosols, but is now mostly desert.

Erosion rates associated with rofabards are reported as the loss of vegetated land with Andosol mantle, measured as hectares per square kilometre per year. This measure of erosion has more meaning for Icelandic landscapes than the traditional tonnes per hectare per year. Estimated losses of Andosol cover in rofabard areas for the whole country are currently about 230 ha a$^{-1}$. This rate is about 10 times lower than the rate needed to cause estimated losses of Andosol mantle in rofabard areas since settlement, 1125 years ago. During peak years of soil erosion, losses were probably several thousand hectares per year, but the erosion rates slowed down as extensive Andosol areas have become barren deserts.


KEY WORDS: Iceland; soil erosion; aeolian processes; rofabards; desertification

## INTRODUCTION

Soil degradation and desertification have devastated large portions of Icelandic ecosystems since the settlement of the island about 1125 years ago. Degradation of such proportions is not known in the other parts of northern Europe, Greenland or the eastern part of the American continent.

Iceland was settled by Vikings, who brought in domestic animals. It is well established that a large portion of the Icelandic deserts was vegetated at the time of settlement. The evidence for this include historical records, Sagas, annals, old farm surveys, old place names, relict areas and current vegetation remnants, pollen analyses, and soils buried under sand (e.g. Einarsson, 1963; Thorarinsson, 1961, 1981; Arnalds, 1987, 1988; Hallsdottir, 1995; Kristinsson, 1995; Gisladottir, 1998). After settlement, rapid population growth led to intensive use of fragile ecosystems. Ecosystem degradation includes both altered vegetation composition due to grazing, cutting and burning of woodlands, and reduced vegetation cover (formation of barren lands, deserts).

Iceland is about 103 000 km$^2$ in area. Classified satellite images show that more than 37 000 km$^2$ are barren deserts with an additional 10–15 000 km$^2$ of disturbed areas with limited plant production (LMI, 1993). At the time of settlement, Icelandic deserts covered only 5000–15 000 km$^2$ and most ecosystems that remain vegetated today were much more productive than they are now. The barren surfaces are often sandy, consisting of volcanic glass, tephra, and crystalline materials that are basaltic, colouring the surfaces dark or black. The desert soils are infertile and generally have 0·5–5 per cent vegetation cover (Arnalds *et al.*, 1987).

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Table I. The Icelandic erosion classification system

| Erosion of Andosols/Histosols | Deserts |
|---|---|
| Rofabards | Melar (lag gravel, till surfaces) |
| Advancing erosion fronts (sand encroachment) | Lavas |
| | Sandur (bare sand, sand sources) |
| Isolated spots | |
| | Sandy lavas |
| Isolated spots and solifluction features on slopes | Sandy melar (sandy lag gravel) |
| Water channels | Scree slopes |
| Landslides | Andosol remnants |

Table II. Erosion severity scale

| Erosion severity | |
|---|---|
| 0 | No erosion |
| 1 | Slight erosion |
| 2 | Moderate erosion |
| 3 | Considerable erosion |
| 4 | Severe erosion |
| 5 | Very severe erosion |

The Agricultural Research Institute (ARI) and the Soil Conservation Service (SCS) made a national survey of erosion and desertification at a scale of 1:100 000 over the period 1991–1996 (Arnalds *et al.*, 1997). The assessment of soil erosion in Iceland is based on classification of erosion forms that can be identified on the landscape (Arnalds *et al.*, 1992, 1994). Comparable methods were employed for mapping erosion in New Zealand (Eyles, 1985) and New South Wales (Graham, 1990). The Icelandic erosion classification system is presented in Table I. Erosion severity is estimated for each of the erosion forms on a scale from zero to five, five being considered extremely severe erosion (Table II). The ARI–SCS erosion database is made of about 18 000 polygons. Each polygon is characterized by one or more erosion forms. A more detailed account of the Icelandic erosion classification system and the national survey of soil erosion was presented by Arnalds *et al.* (1997).

Some of the most striking erosional features of Icelandic landscapes are the 'rofabards', which are erosional escarpments where Andosols are being truncated from the surface and barren desert is left behind. Rofabards are prominent on about 20 000 km$^2$ of Icelandic landscapes and constitute a major erosion problem in the country. Other means of erosion are, however, equally as important in destroying vegetated Andosol ecosystems, especially sand encroachment, but none is as distinctive on the landscape as the rofabards.

## SOILS

Iceland is an island in the North Atlantic Ocean, between 63° and 66° northern latitudes. The climate is humid cold temperate to low arctic. Permafrost is nearly absent. The island is mountainous with lowland areas and river plains along the coastline. Rainfall varies between 600 and 2000 mm a$^{-1}$ in lowland areas.

Volcanic eruptions are frequent and volcanic ash deposits are widespread. The volcanic and glacial deposits are often very unstable and are subjected to intense aeolian activity. Where vegetation stabilizes aeolian materials on the surface, they accumulate on top of the soils. The surface is therefore gradually rising, commonly at the rate of 0·1–1 mm a$^{-1}$ (Thorarinsson, 1961). Deposition of volcanic tephra (ash) during eruptions also contributes to sedimentation on top of the soils.

Glaciers in Iceland cover about 10 000 km$^2$. The sediment load of the glacial rivers is high; large quantities of sediments are deposited on floodplains and at the glacial margins. Some of the interior glaciers cover active volcanic areas. This results in periodic floods of meltwater from subglacial thermal areas that contribute large

 

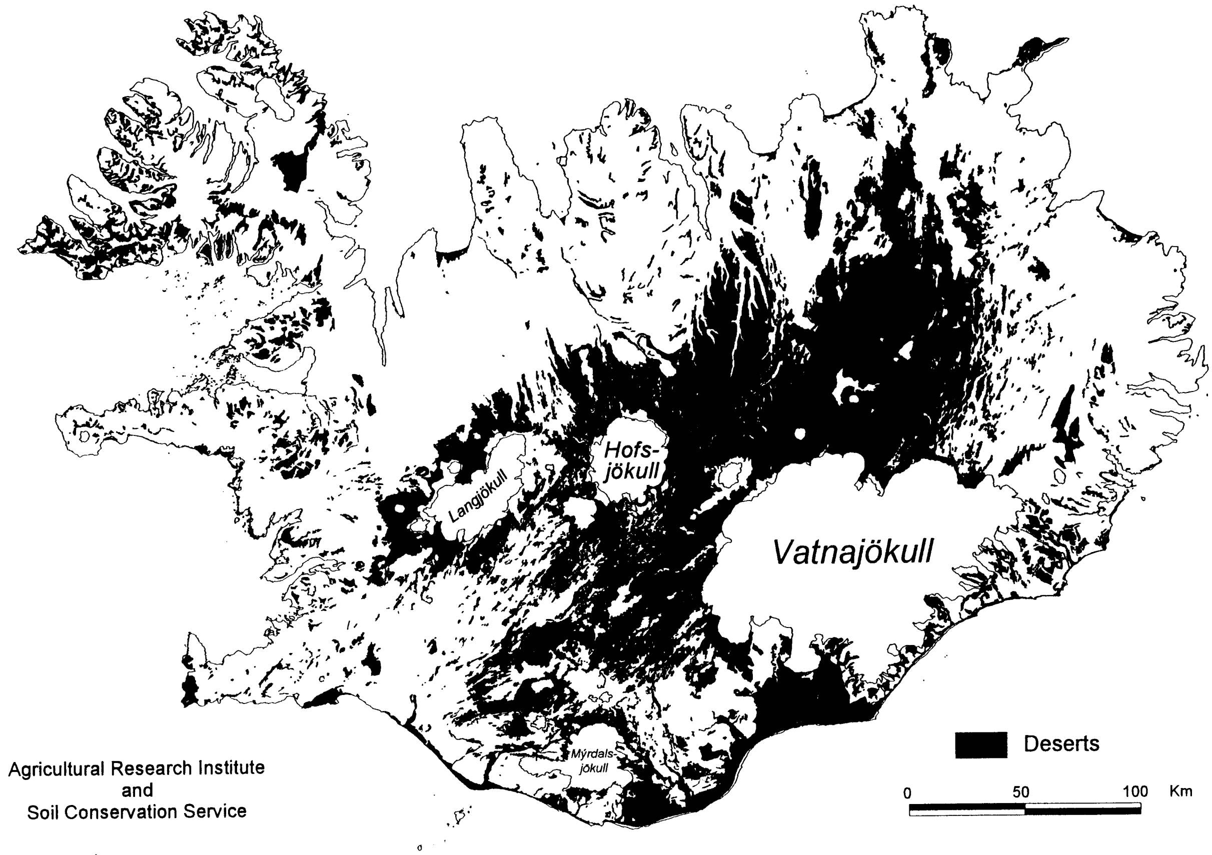


Figure 1. Extent of deserts in Iceland

quantities of silt and sand to aeolian sources at the margins and along floodplains. Catastrophic floods associated with volcanic eruptions are also important contributors to the sand sources (Arnalds *et al.*, 1997).

Soils that form in volcanic ejecta exhibit unique soil properties and are therefore recognized at the order level as Andisols, according to the US Soil Taxonomy (Soil Survey Staff, 1998) or Andosols according to the FAO classification (FAO-UNESCO, 1988). Maeda *et al.* (1977), Wada (1985) and Shoji *et al.* (1993) provided summaries of the properties of Andosols. The parent materials for Icelandic Andosols have sometimes been referred to as aeolian–andic materials (Arnalds *et al.*, 1995). Soils that form in aeolian–andic materials under vegetative cover at freely drained sites are typical Andosols. Wetland soils classify either as Histosols (organic soils) or Andosols. These two soil types characterize about 45 000 km$^2$ (Agricultural Research Institute, unpublished soil map). Soils of barren landscapes are the third overall soil type, comprising a variety of soils, which classify as Andisols, Entisols and Inceptisols according to the US Soil Taxonomy (Arnalds, 1990; Arnalds and Kimble, unpublished data), depending on factors such as the geology and landscape position. The present extent of barren surfaces is between 40 000 and 50 000 km$^2$ (Figure 1), depending on definition.

Some of the properties of Andosols have important implications for erosion. The volcanic parent materials have high surface area and weather rapidly to form such clay materials as allophane and imogolite (Wada, 1985). The Icelandic Andosols have almost no phyllosilicate minerals, such as smectite, that provide cohesion, and the mineralogy is dominated by allophane, imogolite and poorly crystallized ferrihydrite (Wada *et al.*, 1992). The formation of silt-sized aggregates that are susceptible to wind erosion is favoured. The physical characteristics of Andosols include high infiltration rates and hydraulic conductivity, but also high wind erosion susceptibility. They have extremely high water retention, liquid limit and plastic limit, but

Figure 2. A single rofabard. The shape is characteristic of many rofabards, rising steeply with the root mat providing cohesion at the top. This rofabard is within the same area as the rofabard shown in Figure 7

a low plasticity index (Maeda *et al.*, 1977). These properties are characteristic for Icelandic Andosols and they contribute to the high susceptibility of Icelandic Andosols to frost heave, landsliding, and transport by rain-splash and running water.

## ROFABARDS: MORPHOLOGY, FORMATION AND EXTENT

The first part of the Icelandic word rofabard (rof) means erosion and the latter part (bard) connotes the distinctive form of erosion escarpments (Figures 2 and 3). The Andosols lack cohesion and are vulnerable to erosion when exposed to erosion processes, while the underlying materials, typically glacial till or basaltic lava, are resistant to erosion. The materials near the bottom of the Andosols are often weakly cemented, resulting in concave slope profiles. As the erosion progresses, escarpments are formed, with a resistant root mat on top, and resistant materials at the base under the Andosol mantle. Rofabards can have various shapes, with heights ranging from about 20 cm to more than 3 m. An important characteristic of rofabards is that they retain the escarpment form as they retreat. Materials are removed from all of the escarpment bank, and barren desert is left at the new truncated surface. A part of the Andosol materials is blown to the surrounding areas, both vegetated and deserts, but a larger portion is eventually washed into nearby water channels and away from the system, particularly during winter and spring flood events caused by rain storms and rapid snowmelt. The runoff is aided by needle-ice formation, which causes detachment of the uppermost surface layer and makes it extremely susceptible to water removal.

The escarpment banks of the rofabards are darkish brown, often with distinctive volcanic tephra (ash) layers of both basaltic (dark colour) and siliceous (light colour) composition. The age of the tephra layers is usually known, and this permits the use of tephrochronology, dating of soils with volcanic tephra layers (Thorarinsson, 1961). Tephrochronology makes it possible to calculate aeolian deposition rates, which is a valuable tool for studying the history of the aeolian activity.

 

Figure 3. A typical rofabard area. The dark-coloured surfaces are fully vegetated supported by fertile Andosols; the lighter-coloured areas are nearly barren deserts; the rofabard escarpments form the boundary between these two systems. The length (perimeter) of the escarpments can be measured as length per unit area (km $km^{-2}$)

The prerequisite for the formation of rofabards is the gradual build-up of aeolian materials which become Andosols through pedogenesis. As the surface rises, the Andosol mantle becomes thicker and thicker. Underlying the Andosol mantle is the old surface, often glacial till or lava. In the case of till, the aeolian parent materials at the base of the Andosol mantle (right above the till) were deposited soon after the end of the Quaternary glaciation, about 10 000 years ago, but the materials near the surface were deposited recently. It took about 9000 years to accumulate the lower half of the soil mantle but the upper half was deposited during the last 1000 years as a result of accelerated aeolian deposition (often up to 10 times faster) after the settlement (Thorarinsson, 1961).

Rofabards are very noticeable on the landscape. Figure 4 shows the extent of rofabards in Iceland, based on the ARI–SCS soil erosion database (erosion severity 3–5). The thick line defines the present principal rofabard areas (20 250 $km^2$). Their occurrence reflects the distribution of Andosols with thick enough mantles to form the escarpments. The combined belts of deserts and rofabards are also closely associated with the volcanic rift zone cutting through Iceland from the southwest to the northeast. This is because the glacially fed sandy areas and volcanic tephra areas are associated with the zones of volcanic activity.

Currently, the most severe rofabard erosion is at the perimeter of the highland deserts (Figure 1), especially around Langjokull glacier and at the northeastern fringe of the interior deserts. Rofabard erosion is generally most intense in soils that have formed in excessively thick aeolian deposits, commonly exceeding 2 m in northeast Iceland. This thick mantle is more unstable than a thin Andosol mantle, because thick (or high) rofabards have more surface area for lateral wind and rain impact, and the slopes are longer causing more water erosion and saltation impact.

## EROSION PROCESSES

Rofabards have traditionally been attributed to wind erosion processes. Arnalds (1990) emphasized the complexity of processes that occur at each site and the influence of seasonal changes. Figure 5 is adapted

 

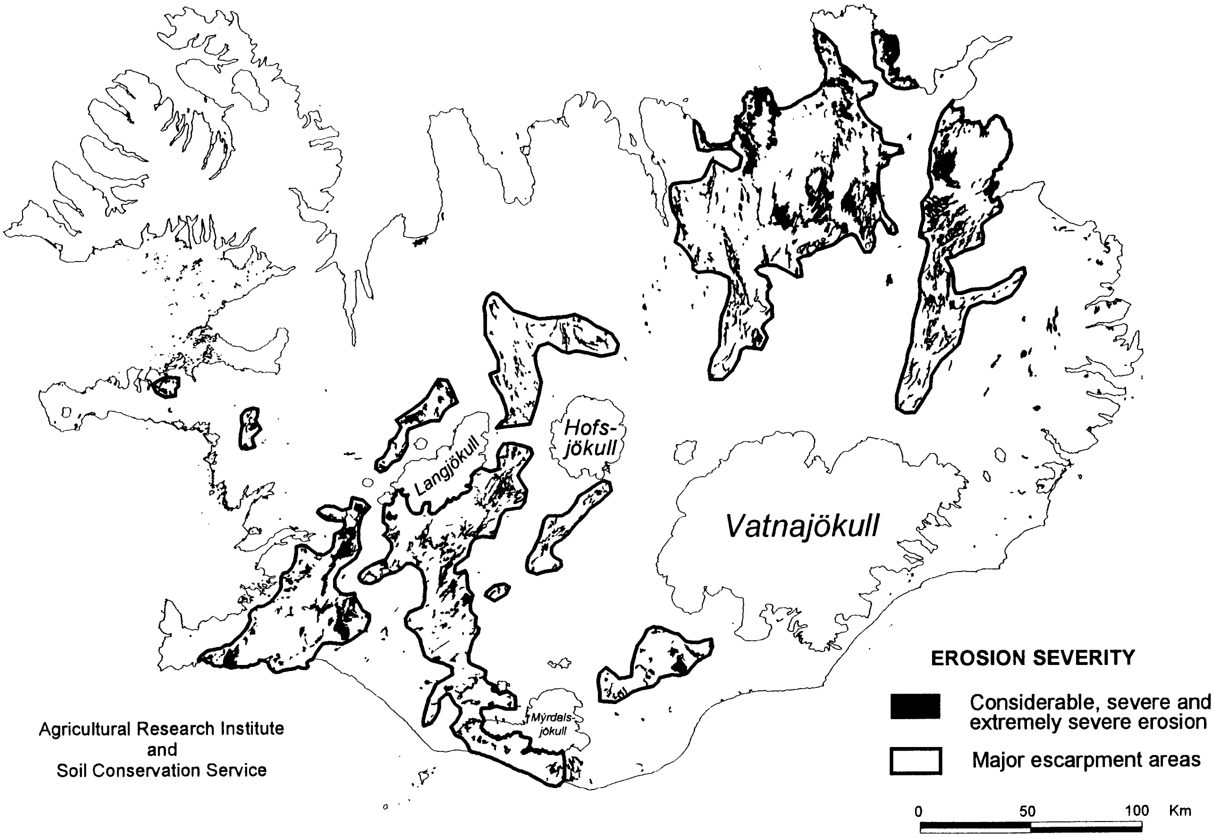


Figure 4. The distribution of rofabards in Iceland

from Arnalds (1990) and indicates the variety of processes that may occur at each site. The dominant erosion mechanism is site specific and time dependent. Wind erosion (saltation) is dominant in the relatively dry areas in northeast Iceland and generally where the escarpments are excessively high ($> 1{\cdot}5$ m). Water erosion is more dominant in southwest Iceland, both rills along the rofabards and lateral rain impact during gale force winds, especially during sudden thaws associated with rapidly moving low pressure areas. Needle-ice formation and freeze–thaw action greatly reduce the cohesion of the surface, making the soil particles easily detached. Sheep commonly use the escarpments for shelter and trampling causes additional detachment from the surface. The root mat eventually becomes undermined, causing slumping. There it gets dispersed and eroded away within a few years, aided by intense freeze–thaw activity.

In many areas, volcanic eruptions have left thick and coarse tephra deposits in the soil profile, especially in the area north and west of Mount Hekla and north of Vatnajokull (see Figure 4). This tephra is unstable, of low density (often about 1 g $cm^{-3}$), and is easily blown by the wind. The abrasion by coarse tephra grains is very effective and intensifies wind erosion at rofabard sites where coarse tephra deposits are part of the soil profile.

In the more humid parts of the country, such as in southern Iceland, cementing of soil materials by silica and/or iron is considerable in the lower part of the profiles. In these settings, the lower portion of the soil is often left behind as the rofabards retreat.

## EROSION RATES

Traditional methods for erosion measurements fall short when it comes to soil erosion on Icelandic rangelands. It is particularly difficult to adopt process-based models since processes occurring at each site are

 

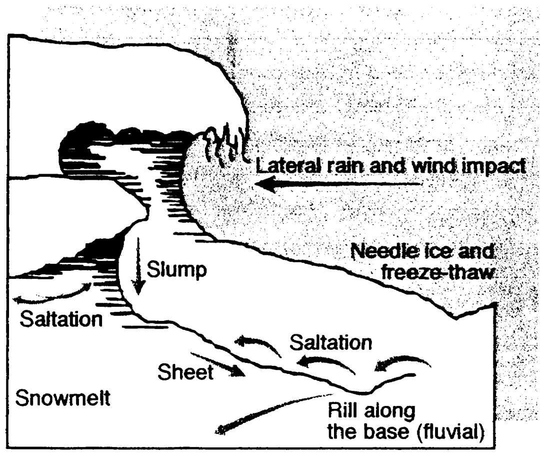


Figure 5. Erosion processes active at a rofabard

quite varied and influenced by seasonal changes. This is especially true for rofabards. In addition, the most commonly used response value for international erosion research, 'tonnes of soil per hectare of land' (t $ha^{-1}$), is not applicable to the Icelandic erosion classification system, which is based on landforms. At rofabards, soil loss measured in tonnes per hectare would mostly be dependent on the thickness of the Andosol mantle. Gullies, landslides and erosion spots (patches of bare soil common in rangelands) are additional examples of erosion forms where tonnes per hectare have limited application.

Discussion of erosion rates associated with rofabards calls for the introduction of several concepts. The loss of productivity of the land and its ecological value is primarily related to the loss of Andosol mantle in Iceland. The most common quantity used for rofabard erosion rates is loss of vegetated Andosol mantle, expressed either as percentage loss per year or as hectares of Andosol mantle lost from each square kilometer of land per year (ha $km^{-2}$ $a^{-1}$). These values adequately describe the losses of fully vegetated Andosol ecosystems, which are replaced by barren surfaces.

To measure rofabard erosion rates, it is necessary to monitor the retreat of rofabards (Figure 6). The retreat (in cm) can be combined with the length of the rofabards per unit area (km $km^{-2}$) to arrive at the area of Andosols that are lost (ha $km^{-2}$ $a^{-1}$). This figure can be converted to tonnes per hectare if the bulk density and the thickness of the andic soil mantle is known.

Fridriksson (1988, 1995) was the first to publish accurate measurements of retreat of rofabards in Iceland. He measured two high and unstable rofabards and found that they retreated at an average rate of 16 cm $a^{-1}$.

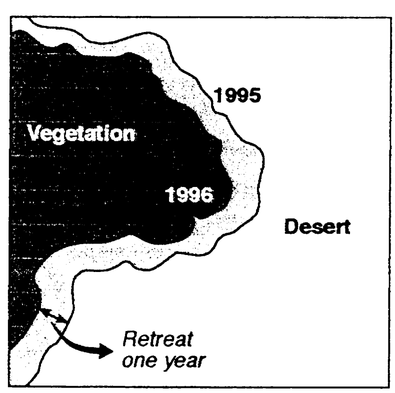


Figure 6. Retreat of a rofabard in one year. Mean retreat rate can be calculated from the lightly shaded area

 

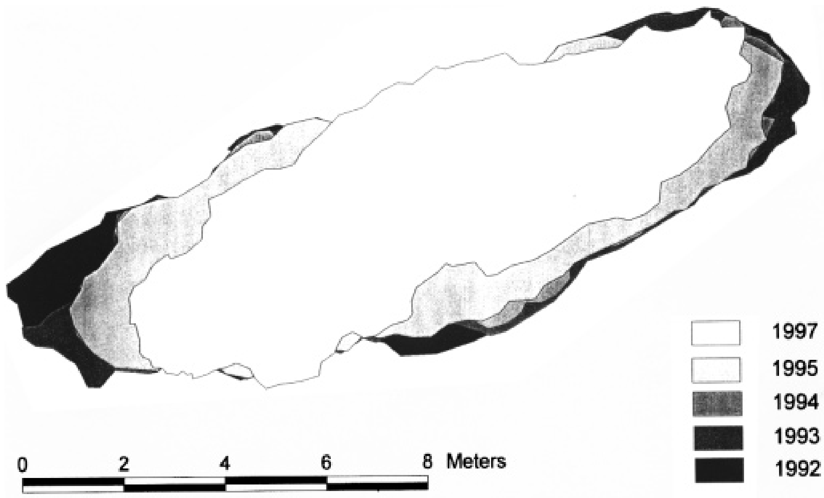


Figure 7. Rofabard retreat. A single Andosol mantle remnant seen from above. Detailed measurements of the rofabard perimeters show how it retreats. The retreat rate is rather fast in this example. See Figures 2 and 4 to visualize rofabards on the landscape

Fridriksson and Gudbergsson (1995) have since added considerable data on retreat rates, showing retreat ranging from less than 1 cm to 26 cm each year. These figures may seem low considering the vast erosion that occurs within rofabard areas; they were somewhat puzzling until measurements were made of the length of rofabards within a given area (km $km^{-2}$). Such measurements show that the length often exceeds 10 km $km^{-2}$, explaining why slow retreat rates at each rofabard can cause rapid losses of vegetative cover. As an example, if the rofabard length is 40 km $km^{-2}$ and the retreat is 10 cm $a^{-1}$, the loss of soil cover is 0·4 ha $km^{-2}$ $a^{-1}$.

The ARI–SCS research group employed two methods for measuring rofabard erosion rates. The first utilized a total station to measure accurately the perimeters of rofabards year after year. The results can easily be plotted and the retreat followed visually (Figure 7). The results of measurements of five rofabards in a 1 ha area in southern Iceland gave an average of 1·5 to 41 cm $a^{-1}$ for each rofabard (Arnalds and Ragnarsson, 1994). These rofabards are isolated remnants of extensive Andosols that used to cover the area. Similar measurements made in northeast Iceland reveal 2–40 cm $a^{-1}$ mean retreat rate (unpublished data). The results are of the same order reported by Fridriksson and Gudbergsson (1995), $<$1–26 cm each year.

The second method used by the ARI–SCS group utilized aerial photographs separated by 20–33 year intervals. Considerable changes are needed in order for them to be detected by comparing aerial photographs, since retreat rates are only of the order of centimetres. Geographical information system (GIS) software can now be used to co-register pairs of photos by automatic classification. Using this method, large areas can be measured as compared to only a few rofabards using field measurements. The results of GIS-based comparisons are presented in Table III. The aerial photographs represent 23–33 year intervals and provide

Table III. Measurement of erosion rates using GIS methods

| Area | Year interval | Size of area ($km^2$) | Retreat (cm $a^{-1}$) | Length of rofabards (km $km^{-2}$) | Loss of Andosol (ha $km^{-2}$ $a^{-1}$) |
|---|---|---|---|---|---|
| Dadastadir | 1960–93 | 0·304 | 3·9 | 46·4 | 0·18 |
| Eilifsvotn 1 | 1961–91 | 0·321 | 3·6 | 49·6 | 0·16 |
| Eilifsvotn 2 | 1960–91 | 0·112 | 3·1 | 55·2 | 0·17 |
| Grjothals | 1960–91 | 0·305 | 8·6 | 51·4 | 0·45 |
| Husavikurfjall | 1960–83 | 1·0 | 1·0 | 21·8 | 0·02 |
| Jorundur | 1960–83 | 0·35 | 6·2 | 92·8 | 0·58 |

 

Table IV. Rofabards; areal extent of erosion severity classes, and rate of erosion.

| Severity class | Extent ($km^2$) | Mean retreat ($cm\ a^{-1}$) | Excarpment length ($km\ km^{-2}$) | Loss of Andosol mantle each year ($ha\ km^{-2}$) | Loss of Andosol mantle each year (ha total) |
|---|---|---|---|---|---|
| 1 | 1735 | 0·3 | 0·5 | 0·0002 | 0·3 |
| 2 | 3511 | 0·7 | 1 | 0·0007 | 2·5 |
| 3 | 1997 | 1·0 | 5 | 0·005 | 10 |
| 4 | 1234 | 5·0 | 15 | 0·075 | 93 |
| 5 | 361 | 10·0 | 35 | 0·35 | 126 |
| Total | 8837 | | | | 232 |

reliable estimates of mean erosion rates for these areas. Areas measured ranged from 0·1 to 1 $km^2$, and the lengths of the rofabards compared were considerable, from 14 to 21 km within each area. This is several orders of magnitude longer than what can be measured by total station on the ground. These areas had escarpment length per unit area ranging between 22 and 93 $km\ km^{-2}$. Results show retreat rates of 1–8·6 cm and overall rofabard erosion rates of 0·02–0·58 ha of Andosol mantle lost from each square kilometre per year within the tested areas.

An attempt was made to estimate total losses of Andosol cover in rofabard areas in the entire country based on the results of erosion measurements discussed earlier, and the extent of erosion severity class for rofabards in the ARI–SCS erosion database (Table IV). The results are an approximation of the current rofabard erosion in Iceland. Such an estimate is also useful in suggesting conceptual means for modelling rofabard erosion. The extent of each severity class in the ARI–SCS database is shown in Table IV, but the total area of rofabard polygons in the database is 8837 $km^2$. Black areas in Figure 4 are rofabard erosion areas (GIS polygons) with erosion severity 3 or greater. The estimated retreat rate for each of the erosion severity classes was estimated based on measurements of retreat rates (Table III; Fridriksson and Gudbergsson, 1995; Arnalds *et al.*, 1994; ARI–SCS, unpublished data). The final parameter needed for this estimate is the length of rofabards on the

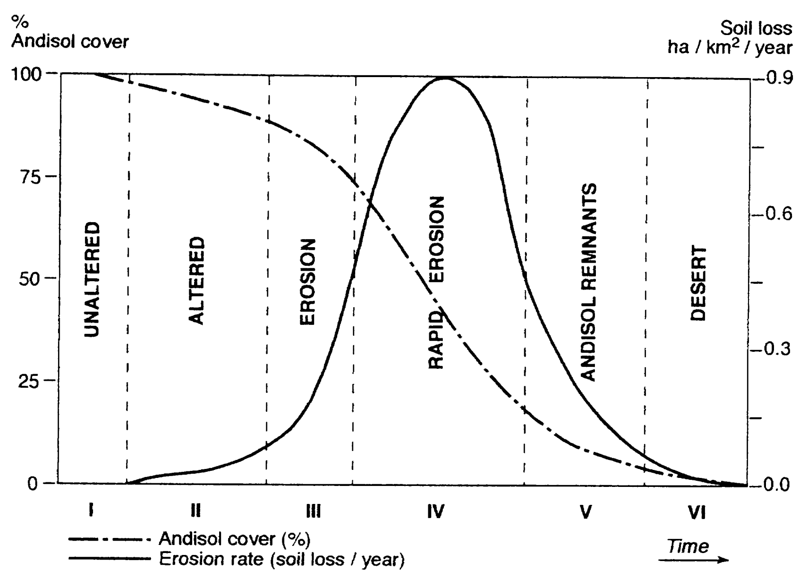


Figure 8. Conceptual model of erosion in a rofabard area. Erosion rate is indicated by a solid line and Andosol cover by a dotted line. The model is modified from Aradottir *et al.* (1992). Erosion (measured as $ha\ km^{-2}\ a^{-1}$) is most rapid at the erosion stage, where the length of escarpments reaches maximum. The numbers are only indicative and represent single rofabard area. Erosion for the whole country would be characterized by two or more major pulses, the time interval would be longer, with lower maximum erosion rate

 

landscape. This was done by combining the GIS measurements for the higher erosion classes, and estimates based on field experience and aerial photographs for the lower erosion classes. These data were used to calculate erosion rates in hectares per square kilometre and total annual areal loss for each erosion severity class (Table IV). The numbers clearly indicate that erosion severity classes 4 and 5 contribute the majority of soil loss. The estimate for overall loss of Andosol cover in rofabard areas of Iceland is about 230 ha $a^{-1}$. This amounts to a total of two to three million tonnes of soil per year, based on a thickness of 1–2 m and bulk density of 0·7 g $cm^{-3}$. Although clearly involving several sources of uncertainty, these calculations suggest the magnitude of this kind of erosion in Iceland.

## DEVELOPMENT OF ROFABARD AREAS

Rofabards are an extreme form of erosion. The initial stage in the development of rofabards is often the formation of isolated spots of bare soil, which can be blown onto the nearby vegetation. The regrowth of vegetation on these spots is hindered by such factors as intense freeze–thaw cycles with needle-ice formation. The development of isolated spots is commonly associated with overgrazing, especially in hummocky terrain. As the spots grow and become more numerous, they can coalesce and become large enough for rofabard to develop. The development is also associated with the formation of water channels on slopes. Knoll and slope positions are susceptible to rofabard development, but soil remnants are often left in depressions of severely eroded areas.

Aradottir *et al.* (1992) provided a qualitative conceptual model for the development of rofabard areas. This model was also explained by Archer and Stokes (1999). Figure 8 is an adapted version of this model where erosion rates have now been provided on the y-axis. Fridriksson (1988) presented similar conceptual graphs with his first figures for erosion rates. Figure 8 shows six successive stages of degradation from mere vegetation composition changes and formation of isolated erosion spots to rapid erosion along rofabards exceeding 50 km $km^{-2}$. The final stage is desert. Erosion rate (solid line on Figure 8) increases as the length of rofabards increases, but decreases when the Andosol cover has been reduced considerably (dotted line).

The ARI–SCS erosion database suggests that 15 000–20 000 $km^2$ of present-day desert became barren because of rofabard erosion. Most of this erosion has occurred during the past 1125 years since Iceland was settled. There are in addition 5000–10 000 $km^2$ where sand encroachment and rofabard retreat cannot be separated as major processes based on current knowledge, especially in the sandfields north of the Vatnajokull glacier.

If 15 000 $km^2$ of Andosol mantle have been desertified over the past 1125 years, the average loss would be about 1360 ha $a^{-1}$. The area desertified by this mode may even be larger, resulting in a still higher figure for annual losses. The present erosion rates associated with rofabards (about 230 ha $a^{-1}$) therefore do not adequately explain estimated losses of Andosols for the past 1125 years since settlement, even though some of the erosion may have started earlier. The relatively low current rate, and the large extent of the area that has become desertified, suggest that losses of vegetative cover at rofabard areas were on the order of several thousand hectares per year when loss reached maximum. The rate of soil loss has since been reduced by one order of magnitude as extensive areas have become almost totally desertified leaving only the rofabard soil remnants in depressions. Tephrochronological studies can be used to study aeolian deposition between volcanic tephra layers of known age. The deposition rates are indicative of soil erosion within the study area. Such studies in south Iceland indicate that maximum aeolian activity occurred during the 12th and 13th centuries and again during the 17th, 18th and 19th centuries (Sigbjarnarson, 1969).

The model in Figure 8 assumes erosion rates up to 0·9 ha $km^{-2}$ $a^{-1}$, which is higher than the ARI–SCS group measured in rofabard areas where erosion is considered very severe. This high rate is chosen because it is likely that the soils in the remaining erosion areas are more resistant to erosion than those that were desertified long ago. Soils with thick non-cohesive coarse tephra layers near the most active volcanoes and thick unstable soils influenced by intense aeolian activity near glacial margins and floodplains would have been most susceptible to erosion. Most of such areas have now lost the Andosol mantle and are barren deserts. The assumed timescale in Figure 8 for a given area (e.g. 100 $km^2$) would be of the order of several hundred

 

years. It should be kept in mind that the nature of this model is conceptual although numbers are indicated on the y-axis.

The causes for the development of rofabards and subsequent desertification are primarily related to the use of the land. Cooling trends that began 2500 BP, and growing sources for aeolian sand associated with the formation of glaciers, may be primary factors in some areas, especially along the coastline and near glacial margins at higher elevations. Major change with accelerated erosion occurred at the time of settlement 1125 years ago. Tephrochronological studies show that aeolian deposition was accelerated soon after settlement in AD 874 (e.g. Thorarinsson, 1961; Haraldsson, 1981), particularly in the highlands. There is no documented evidence for such massive country-wide erosion in Iceland before settlement.

The impact of land use was very detrimental for several reasons. Icelandic ecosystems are extremely vulnerable to erosion because of non-cohesive soils, intense cryoturbation processes, periodic cold spells and tephra deposition (Arnalds, 1990). The vegetation is fragile and its resilience to disturbance and climatic fluctuations is greatly affected by grazing and wood cutting (e.g. Gisladottir, 1998). There was a cooling trend after AD 1200 (Bergthorsson, 1969). The cooler climate resulted in larger glaciers that caused an increased number of meltwater floods and larger unstable sandy areas at glacial margins and flood plains ('sandar'). Increased aeolian processes on these unstable surfaces also play an important role in addition to man's influence on the ecosystem as they made the Andosol mantle thicker and therefore more unstable than it was before. It can be argued that the combination of these factors caused a 'snowball effect' that greatly accelerated erosion rates. It should, however, be stressed that further research is needed to adequately document the history of rofabard soil erosion in Iceland, including the processes involved and the interaction of causes.

## CONCLUSIONS

The ARI–SCS soil erosion database provides reliable information about the extent and severity of present rofabard erosion in Iceland. Rofabards are common erosional features that cause losses of soils and vegetated ecosystems at the rate of several hundred hectares per year. The cause for their formation is primarily land use, but natural factors also play an important role. Increased aeolian activity after settlement resulted in a thicker Andosol mantle that makes the soils more vulnerable to erosion.

Rofabard areas were more extensive in historic times than before the settlement of Iceland, over 1100 years ago. Erosion rates may have been as high as several thousand hectares of Andosol cover lost each year. Rates of vegetation and Andosol cover loss have declined as extensive rofabard areas have become almost totally desertified.

Relating these numbers to more conventional means of expressing soil erosion, soil loss from present-day rofabard areas is two to three million tonnes per year, but may have reached >30 million tonnes per year during historic times.

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